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Composition studies of Ultra High Energy Cosmic Rays at the Pierre Auger Observatory

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Abstract

To understand the origin and nature of Ultra High Energy Cosmic Rays their mass composition must be known. The Pierre Auger Observatory is an instrument which provides valuable information for the determination of the primary mass. Different parameters that describe various characteristics of the shower development and at the same time are sensitive to the primary mass are discussed. Their energy dependence and a comparison with predictions from different models are also presented.

Keywords: UHECR, Pierre Auger Observatory, Composition

1. Introduction

The composition of ultra-high energy cosmic rays (UHECRs) is not yet fully understood. The Pierre Auger Observatory is a powerful hybrid cosmic ray detector that consists of two parts: a Fluorescence Detector (FD) [1] which allows one to measure the longitudinal profiles of cosmic ray induced showers as well as a Surface Detector array (SD) to measure the lateral distribution of particles [2].

The atmospheric depth where the longitudinal development of the air shower reaches the maximum number of particles, called $X_{\max}$, is a standard observable used to extract composition information as different nuclei produce different mean values of $X_{\max}$ and different dispersions in $X_{\max}$ [3, 4]. Conversion of the average of $X_{\max}$ in terms of mass (A) is inferred through air-shower simulations.

In addition to the $X_{\max}$ approach, the Auger Collaboration has proposed different methods [5] to infer masses that take advantage of the large statistical sample provided by the high-duty cycle of the SD array through the measurement of observables related with muon content.

In this paper we summarize the recent results concerning the mean value of $\ln A$ and its variance ($V(\ln A)$) obtained from $X_{\max}$, as well as the results of the fit fraction using the complete $X_{\max}$ distribution. Also we show the latest results of muon studies that allow us to constrain the hadronic interaction models through the muon production depth parameter and the muon number in highly inclined events.

2. Depth of the shower maximum and mass composition implication

According to the superposition model [6], $\langle X_{\max}\rangle$ is linear in $\langle \ln A\rangle$ and therefore it actually measures mass composition for both pure and mixed compositions. However, the behaviour of $\sigma(X_{\max})$ is more complex to interpret as there is no one-to-one correspondence between its value and a given mean log mass. Only in the case of pure composition this correspondence is unique.

The Pierre Auger Collaboration has published results on the mean and dispersion of the $X_{\max}$ distribution

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at energies above 10^{18} eV [7, 8] as shown in Figure 1. The analysis method originally proposed by Linsley [7, 9, 10] was refined and applied to Auger data to convert those observables to the first moments of the log mass distribution, namely $\langle \ln A \rangle$ and $V(\ln A)$ [4]. Results analyzed using Sybill 2.1, EPOS-LHC and QGSJETII-04 are shown in Figure 2. From the comparison between models, it is shown that energy evolution is still common to all models and the average mass increases with decreasing log mass dispersion. The EPOS LHC model is compatible with observations but QGSJETII-04 model leads to results in the unphysical region for some energies.

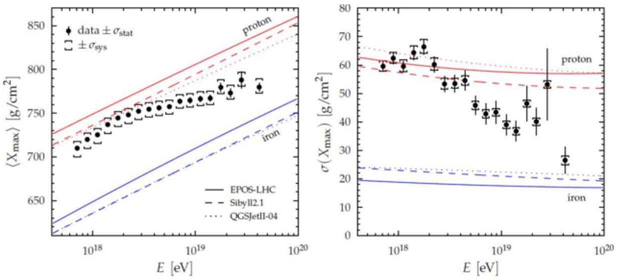

Figure 1: Energy evolution of the first two central moments of the X_{max} distribution compared to air-shower simulations for proton and iron primaries [3].

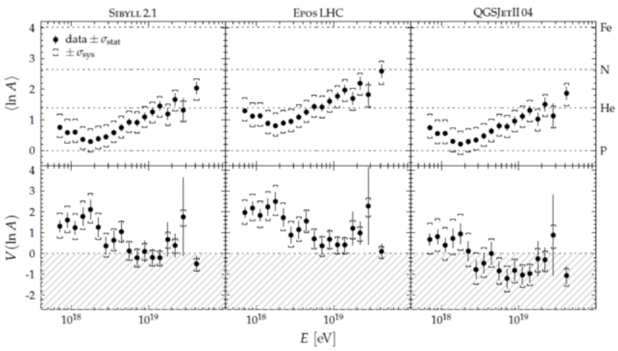

Figure 2: Average of the logarithmic mass and its variance estimated from data using different interaction models. The non-physical region of negative variance is indicated as the gray dashed region [3].

Another approach presented is based on the full X_{max} distribution. This approach maximizes the information and reduces possible degeneracies that can occur when one considers only the first two moments of the X_{max} distribution. For a given hadronic interaction model, the X_{max} distribution is compared to predictions made using Monte Carlo (MC) simulations formed with varying nuclear fractions, and a binned maximum-likelihood discriminator is used to choose the best-fit fractions [12]. The hybrid X_{max} dataset in the range $E = 10^{17.8} - 10^{20}$ eV measured by the Auger Collaboration was used to determine whether it can be described satisfactorily by an evolution of composition with energy. First it was considered as a mixture of the two most stable types of particles, protons and iron nuclei, and the fits were extended to include extra components. Specifically, helium and nitrogen nuclei were included as representatives of the intermediate range of nuclear masses.

The fit quality is measured by the p-value, which is defined as the probability of obtaining a worse fit (larger likelihood) than that obtained with the data, assuming that the distribution predicted by the fit results is correct [12]. The two component fit approach gives poor quality fits, which indicates that none of the hadronic interaction models can describe the data as a simple mixture of protons and iron nuclei. The fit result for the mix of protons, helium, nitrogen and iron is shown in Figure 3. Adding intermediate components greatly improves the fits for all hadronic interaction models. Results shown in Figure 3 using EPOS-LHC in particular are satisfactory over most of the energy range.

From the results of X_{max} and its fluctuation it is possible to say that, despite the differences in the chosen models, we found above $10^{18.3}$ eV an evolution from light to intermediate masses and a decreasing of $V(\ln A)$ over the whole energy range. With respect to the full distribution of the depth of the shower maximum, using the current hadronic interaction models we found it to be inconsistent with a composition dominated by protons, nor can they support a large contribution from iron nuclei. Introducing intermediate masses to the fits produces acceptable fit qualities for some of the hadronic interaction models used. Though the fitted compositions are in general model-dependent, all three models considered gave similar results for the evolution with energy of the proton fraction. However, it is still possible that the observed trend is not due to an evolution of composition mix, but rather to deviations from the standard extrapolations in hadronic interaction models.

3. Muons in air showers at the Pierre Auger Observatory

The number of muons in an air shower is another powerful tracer of the mass. Simulations show that the produced number of muons, N_μ, rises almost linearly with the cosmic ray energy, and increases with a small power of the cosmic ray mass. This behaviour can be

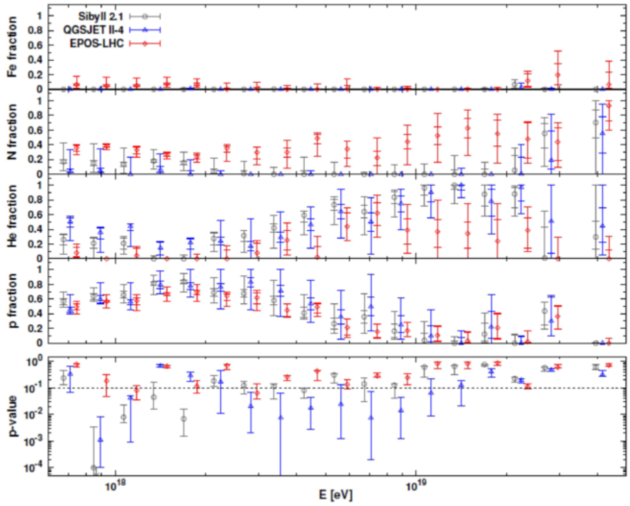

Figure 3: Fitted fraction and quality for the scenario of a complex mixture of protons, helium nuclei, nitrogen nuclei and iron nuclei from bottom to top. The upper panels show the species fractions and the lower panel shows the p-values [12].

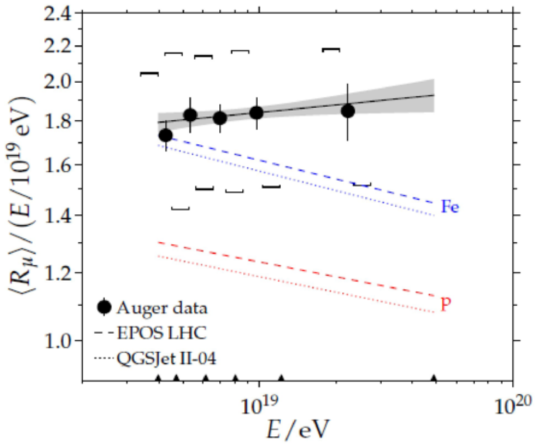

Figure 4: Average muon content $\langle R_\mu \rangle$ per shower energy E as a function of the shower energy E in double logarithmic scale. Data is shown in bin-by-bin circles together with the fit (line) [13]. Square brackets indicate the systematic uncertainty of the measurement, the diagonal offsets represent the correlated effect of systematic shifts in the energy scale. The grey band indicates the statistical uncertainty of the fitted line. Shown for comparison are theoretical curves for proton and iron showers simulated at 67° (dotted and dashed lines). Black triangles at the bottom show the energy bin edges. The binning was adjusted by an algorithm to obtain equal numbers of events per bin.

understood in terms of the generalized Heitler model of hadronic air showers [11, 13, 14]. Muon density in the shower plane is used to obtain the muon number in inclined air showers using the relative scale factor called N_{19}. This value is defined as the relative measure of the produced number of muons at a given zenith angle [13]. With this parameter it is possible to obtain the normalized muon content per shower as a function of the shower energy called R_μ. The muon content R_μ of individual showers with the same energy and arrival direction varies. This is caused by statistical fluctuations in the development of the hadronic cascade, and, in addition, by random sampling from a possibly mixed mass composition. We refer to these fluctuations combined as intrinsic fluctuations. In the following, we make statements about the average shower, meaning that the average is taken over these intrinsic fluctuations.

The results for the parameter $\langle R_\mu \rangle$ are shown in Figure 4, where square brackets indicate the systematic uncertainty of the measurement and the grey band indicates the statistical uncertainty of the fitted line. The theoretical curves are shown for comparison for proton and iron showers simulated at 67°. These results show that the proton and iron showers are well separated, which illustrates the power of $\langle R_\mu \rangle$ as a possible composition estimator.

The other parameter presented comes from the reconstruction of the distribution of muon production depths (MPD). Since muons come from the decay of pions and kaons, the shape of the MPD distribution contains information about the evolution of the hadronic cascade. This distribution is characterized by a parameter called $X^\mu_{\max}$ that is the point along the shower axis where the production of muons reaches its maximum as the shower develops through the atmosphere. The results of $X^\mu_{\max}$ are presented in Figure 5 [15].

From $X^\mu_{\max}$ results, the current level of uncertainties associated with the parameter and simulations prevents us from making conclusive statements on mass composition. However, it is possible to say that the maximum of the the $X^\mu_{\max}$ distribution also provides information to constrain hadronic models.

For R_μ a hint of a discrepancy between the models and the data is the high abundance of muons in the data. In addition, both observables presented favour a transition from lighter to heavier elements in the considered energy range.

4. Conclusion

Parameters obtained with FD and SD detectors of the Pierre Auger Observatory allow one to extract information about mass composition as well as constrain

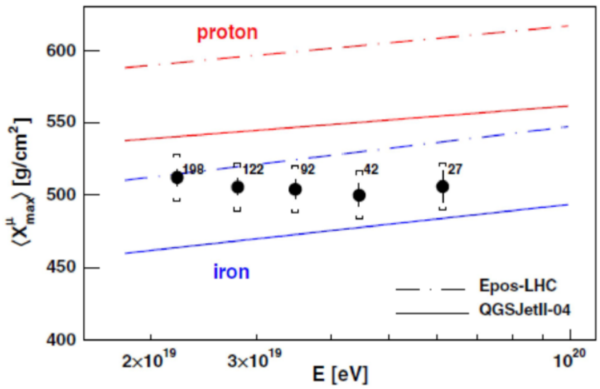

Figure 5: $X^{\mu}_{\rm max}$ as a function of energy. The predictions of different hadronic models for protons and iron are shown. Numbers indicate the number of events in each energy bin, and brackets represent the systematic uncertainty [15].

the hadronic and improve interaction models. The measurements presented here show in general a trend towards an increasing fraction of heavier primaries with energy and a deficiency in the models to describe the muon production content in the shower.

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